

SOME NEW MEASURES OF SUPRAGLOTTAL AIR PRESSURE
AND THEIR ARTICULATORY INTERPRETATION

By

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TABLE OF CONTENTS

	<u>Page</u>
ACKNOWLEDGMENTS	ii
ABSTRACT	iv
INTRODUCTION	1
PROCEDURE	8
RESULTS	22
DISCUSSION	40
SUMMARY AND CONCLUSIONS	76
APPENDIX	79
BIBLIOGRAPHY	91
BIOGRAPHICAL SKETCH	94

Abstract of Dissertation Presented to the Graduate Council
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Five male subjects produced isolated VCV's-- where C is the stop consonants /p, b, t, d/ and V is the vowel /a/ or /i/--while apparatus for the simultaneous recording of supraglottal air pressure (P_0) and air flow. The point in time when air flow reached zero (i.e., complete closure at the consonantal point of articulation) and abruptly ascended from zero (i.e., consonantal release) were identified on the P_0 trace. These points were then used as a physiological reference from which other measures of the P_0 waveform were made. These measurements included: The duration of the closing phase, occlusion phase and release phase; the P_0 magnitude at the instant of closure and release; the peak magnitude of P_0 ; and both quantitative and qualitative estimates of waveform shape. The data were analyzed using a factorial analysis of variance for both main effects and interactions (subjects X consonants X vowels).

The results indicated that vowel environment affected the duration of the closing and release phase while having little affect on the

duration of the occlusion phase and the P_0 magnitude and waveform. Place of articulation (i.e., bilabial vs apical alveolar) had no systematic effect on the temporal, magnitude or waveform measures. Comparisons as a function of manner (i.e., voiced versus voiceless stops) indicated that voiceless stops generally had greater pressure magnitudes at the instant of closure, a longer release duration and a more convex waveform.

With the aid of a computer simulated model of VCV production, an articulatory interpretation of these results was attempted. It was concluded that 1) homorganic stops have similar gestures at the point of articulation and that this gesture is affected by vowel environment, and 2) that the resulting P_0 magnitude and waveform is associated with various articulatory mechanisms which facilitate the voicing and devoicing of stop consonants.

INTRODUCTION

Those speech sounds which are considered by their manner of production as stops have generated a considerable amount of research interest for a number of years. Such consonants are very common in many languages of the world. In fact, most spoken languages employ a class of speech sounds having a mechanism that can be grossly described as the creation of a pulmonic pressure difference across a sudden occlusion somewhere in the vocal tract, followed by a sudden release due to the relatively fast opening of the occlusion. In the terminology of physiological phonetics, the above description roughly delimits the class of American English stops (/b,p,d,t,g,k/). It has been common practice to linguistically categorize stops according to several different dichotomies: voiced/voiceless or tense/lax or aspirated/unaspirated. However, it is generally agreed that no single classification is adequate, but rather, the three characteristics must be taken collectively to realistically and adequately define the physiological/acoustic nature of stops (Kim, 1965; Fant, 1966, 1969; Fisher-Jørgansen, 1968; Lindquist and Lubker, 1970). That is, the subset /p,t,k/ contains voiceless/aspirated/tense stops, while /b,d,g/ are voiced/unaspirated/lax stops. However, for the purpose of discussion, the terms voiced/voiceless will be used to denote the /p,t,k/-/b,d,g/ distinction.

The linguistic confusion regarding the terminology of stop consonant classification is, in part, a reflection of the extent to which we understand the physiological/acoustic nature of these consonants. Stop consonant production employs a very complex articulatory synergism as

demonstrated by the comparatively large number of dynamic and concomitant peripheral gestures it incorporates. It has been necessary, therefore, to study stop consonants from various orientations and utilizing sundry techniques. One widely used method is the recording of the low frequency variations in supraglottal air pressure (P_0) during stop production. Because such variations in P_0 reflect the superposition of a host of articulatory variables (e.g., respiratory effort, glottal resistance, pharyngeal expansion, resistance at place of articulatory occlusions) researchers have utilized measures of P_0 as an indicator of articulatory variability as a function of phonemic classification, stress environment, syllable utterance rate, vocal intensity and linguistic boundaries. Naturally, it has been necessary in the course of such studies to apply some measurement scheme to the continuous time-varying nature of the P_0 pulse. The measurand most often reported in the research literature is peak supraglottal air pressure (P_k). Other measurands reported with less frequency are: Duration of the P_0 rise (T_r) and decay (T_d) time, total duration of the P_0 pulse (T_t), and maximum value of the integral of the pressure ($\int P$). These measurands are summarized in Figure 1.

On the basis of such measures, P_0 has been found to vary as a function of various contexts and conditions. Specifically, a number of studies have shown that voiceless stops (/p,t,k/) have larger P_k 's and $\int P$'s, and longer T_t 's and T_r 's than their voiced counterparts (/b,d,g/, respectively) (Black, 1950; Stetson, 1951; Subtelny et al., 1966; Malecot, 1966, 1968, 1969; Arkebauer et al., 1967; Soda et al., 1967; Brown and McGlone, 1969a, 1969b; Lubker and Parris, 1970; Brown et al., 1970; Lisker, 1970). These same effects hold with slightly less generality as the analyzed samples become more complex due

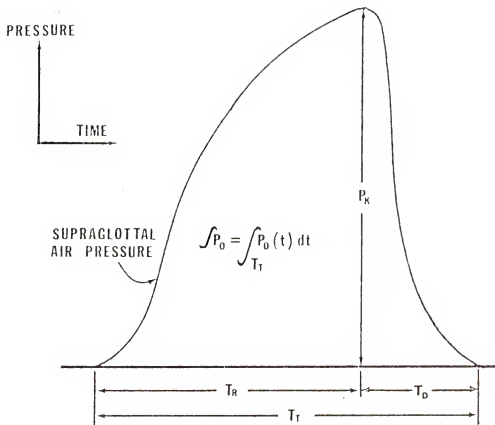


FIGURE 1. The five measures of supraglottal air pressure previously reported in the literature: Peak pressure (P_K), integral of the pressure pulse ($\int P_0$), total duration of the pulse (T_T), and its rise (T_R) and decay (T_D) time.

to alterations in the phonemic and stress environment as well as the sequential position of the stop consonant within the sample utterance (Black, 1950; Malecot, 1955; Subtelny et al., 1966; Brown and McGlone, 1969a; Brown et al., 1970; Lisker, 1970).

The effects of syllabic rate and vocal intensity have also been investigated. Increasing vocal intensity results in an increase in P_k for stops in the utterance -initial, -medial, and -final position (Stetson, 1951; Subtelny et al., 1966; Soda et al., 1967; Arkebauer et al., 1967; Brown and McGlone, 1969a; Malecot, 1969; Brown, 1969; Leeper and Noll, 1972). Generally T_t increases only when stops are in the medial position (Soda et al., 1967; Malecot, 1969). Reports regarding the results of increasing syllabic rate on P_k are contradictory. For the range of rates which might be considered slow to medium Brown and McGlone (1969a) found no significant difference (between 1 syllable/sec and 3 syllables/sec), and similarly Malecot (1969) reports no significant difference between rates of 2.5 and 3.0 syllables/sec; however, Arkebauer et al. (1967) found a significant increase in P_k between rates of 2 and 4 syllables/sec. With regard to syllable rates within the medium -fast range, Malecot (1969) found no difference between rates of 5 and 7.5 syllables/sec regardless of the position, while $\int P$ decreased significantly only for stops in the medial position. Brown (1969) also found that the $\int P$ for intervocalic stops (i.e., medial position) decreased as rate increased from 1 to 3 syllables per second; however, no change was found between 3 and 6 syllables/sec.

Because researchers at this time are unable to map the complex time-varying nature of $P_o(t)$ (even as summarized by the types of measurements reported above) on articulation, the physiological explana-

tion for the P_0 variations discussed above cannot be derived directly from the pressure trace. For example, the simple P_k difference between voiced and voiceless stops may be explained in articulatory terms by hypothesizing differential effects (both in magnitude and timing) due to glottal resistance, active pharyngeal volume changes, respiratory effort, the impedance of the walls of the supraglottal cavity, incomplete velar-pharyngeal closure. Clearly, all of these factors may affect the P_k of a stop; however, which one (or ones) cause voiced stops to have lower P_k 's than voiceless stops? Presently, the answer cannot be derived directly from the pressure measurements. It has been necessary, therefore, for researchers to investigate directly those particular articulatory aspects of stop production that have been hypothesized (on the basis of P_0 and other indirect measures of articulation--e.g., air flow and subglottal air pressure) as major factors relating to P_0 variation.

Briefly, such studies have shown that: (1) a number of simultaneous articulatory co-gestures concomitant with the gesture at the major point of articulation--i.e., the formation of the occlusion and its release--are active during plosive production, and (2) the occurrence or magnitude of these subgestures is generally distributed along the voiced-voiceless dimension. Specifically, it has been reported that average glottal area usually increases during the production of intervocalic voiceless stops while voiced stops show little change in average glottal area (Kim, 1970; Sawashima, 1970; Lisker et al., 1970; Dixit and MacNeilage, 1974). Similarly, pharyngeal volume and laryngeal depression also appear to have significantly greater magnitudes during voiced (as opposed to voiceless) stop production (Perkell, 1969; Kent and Moll,

1969; Bell-Berti and Hirose, 1972). Finally, Cooker (1963) has demonstrated that the respiratory system may play an active role in the production of stop consonants at low syllabic rates.

Some additional physiological factors that may also influence P_0 are the impedance of the walls of the supraglottal cavity, incomplete velar-pharyngeal closure, and the resonant affects of the subglottal system. Rothenberg (1968) found that the walls of the supraglottal vocal tract are more compliant during voiced stop production. His data compare well with the tissue impedance measurements made by Ishizaka et al. (1974) on tense and relaxed musculature. In his investigation of nasal air flow, Lubker (1973) concluded that the velar pharyngeal port is probably tightly sealed during stop production. Finally, based on the performance of a model of stop production, Rothenberg (1968, pp. 56-62), concluded that under certain articulatory conditions the resonant effects of the respiratory system may influence the time-course of P_0 .

Recently, there have been some attempts to understand the complex relationship between the physiological variables mentioned above and the reported variations in P_0 by utilizing simulation techniques (Rothenberg, 1968; Mermelstein, 1971). While such synthesis techniques allow one to deal mathematically with the complex time-varying nature of the articulatory co-variables of consonant production and their aerodynamic effects, precise input information regarding the timing and magnitude of the articulatory gestures is necessary. Moreover, one must have detailed information regarding the anticipated aerodynamic effects to test the validity of the simulation. At present, information concerning at least one aerodynamic variable, $P_0(t)$, does not meet

this requirement primarily because:

- (1) It is incomplete with regard to the amplitude dimension--
 $P_O(t)$ is a continuous time-varying function. While amplitude may be measured any place along this function only the peak magnitude of the pressure (P_k) has been reported. P_k , of course, does not reflect the $P_O(t)$ variation that precedes or follows it.
- (2) Its temporal relationship to articulation is unknown--
 there has been no indication in the research literature of how the various measures of $P_O(t)$ are timed in relation to any of the concomitant articulatory gestures of stop consonant production. For example, does P_k occur at the point in time of articulatory release of the plosive?...before the release?...after?

Therefore, the purpose of this investigation was to:

1. Develop a measurement scheme which would: a) more adequately describe the time-variant nature of supraglottal pressure variation during stop consonant production, and b) indicate the temporal relationship between these aerodynamic measurands and the physiological dynamics at the consonantal point of articulation.
2. Describe the effect of manner (voiced/voiceless), place of articulation (bilabial/apical alveolar) and vowel environment (/a,i/) on supraglottal air pressure in terms of these new measurands.
3. Discuss the relationship between the time-varying nature of supraglottal air pressure and articulatory dynamics.

PROCEDURES

Subject Related Procedures

Five young adult male speakers of General American English served as subjects. Each subject produced six repetitions of each VCV combination -- where C was the consonant /p/, /b/, /t/, or /d/, and V was the vowel /a/ or /i/ -- and was instructed to a) sustain the vocalic portions of the VCV for at least one second, b) place equal stress on each syllable, c) produce each repetition of the VCV on a separate respiratory expiration, d) use his normal pitch, and to speak at a conversational level. The order in which the speech samples were spoken was varied for each subject. Several sessions were held during which each subject practiced producing the speech samples according to the instructions above while wearing the pressure and air flow apparatus described below. A photograph of the experimental set-up is shown in Figure 2.

Instrumentation

Supraglottal air pressure (re: atmospheric pressure) was sensed via a Statham PM131TC differential pressure transducer and subsequently amplified filtered and recorded on a Honeywell Visicorder (Model 1508A) using the equipment shown in Figure 3. The oral air pressure was transmitted to the transducer via a polyethylene probe tube 38 cm in length and with an inside diameter of 0.178 cm and an outside diameter of 0.279 cm. Each probe tube was custom shaped to fit the pre-

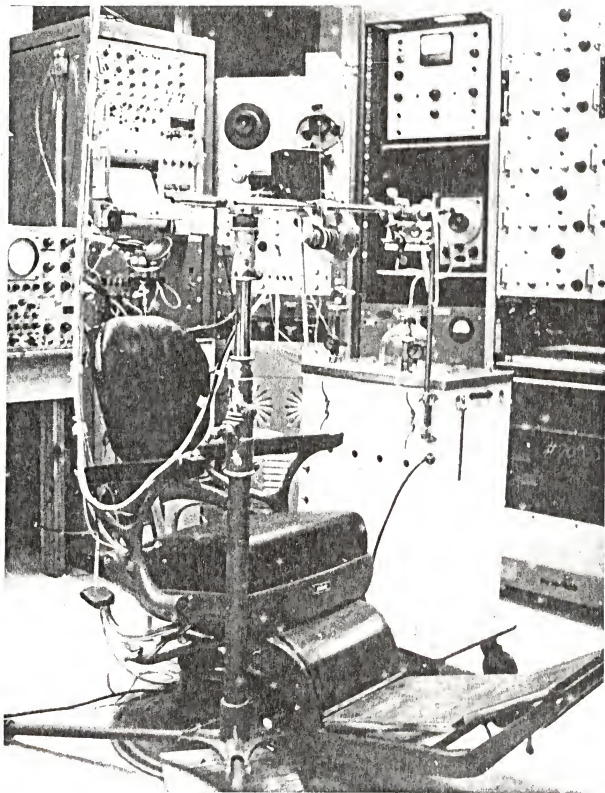


FIGURE 2. Photograph of the experimental set-up.

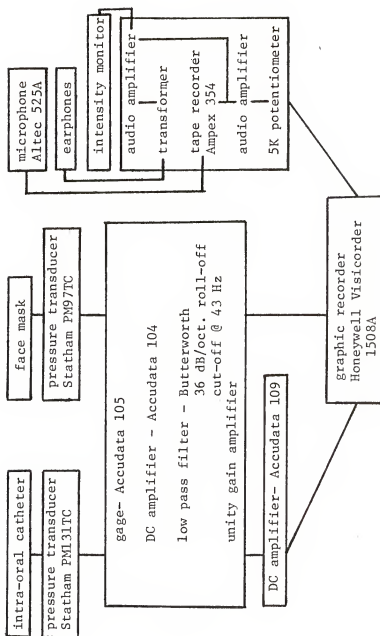


FIGURE 3. Equipment used for the simultaneous recording of supraglottal air pressure and air flow during the production of isolated VCW's.

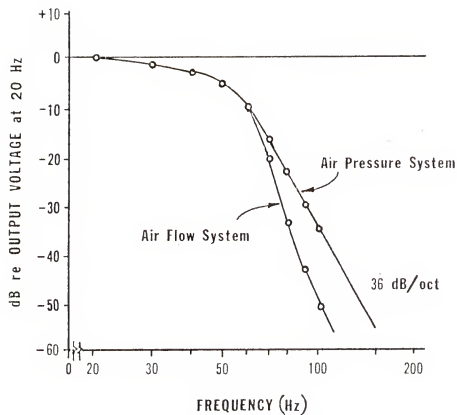


FIGURE 4. Frequency response of the air flow and air pressure transducing systems.

maxillary arch of each subject using the methods described in Brown (1969), thus insuring a minimum of interference with articulation (see Figure 5).

Static calibration of the pressure measuring system was performed with a U-tube manometer in the method described by Fry (1960) and found to be linear within the pressure range of interest. These values were later used to generate conversion factors for the pressure measures made from the graphic recordings. Dynamic calibration of the pressure system was performed using the equipment and procedures described by Edmonds et al. (1971). The frequency response¹ of the system (including the probe tube) is presented in Figure 4.

The air flow at the lips during the production of the VCV samples was simultaneously recorded for the purpose of temporally identifying the instant of complete closure and release at the point of articulation; i.e., the instants in time when the volume velocity reached and ascended from zero volume velocity during the consonantal occlusion. For this purpose, subjects wore a face mask similar to the one described in Klatt et al. (1968). The difference in pressure between the interior of the mask and atmospheric pressure (which is proportional to the flow through the mask²), was sensed via a Statham

¹During a pilot study in preparation for this research, it was determined that the time constant of the pressure system (approximately 20 msec) was always much shorter than the estimated time constant of the supraglottal air pressure pulse.

²The air flow through the face mask may be considered incompressible because the dimensions of the face mask are much smaller than the wave lengths under study, and the volume velocities are very small compared to the speed of sound. The volume velocity and pressure drop across the mask are, therefore, linearly related as expressed by the Bernoulli equation for incompressible flow. By the same argument, the graphic recording of the supraglottal air pressure and volume velocity traces are in temporal synchrony.

PM97TC differential pressure transducer. The transduced pressure signal was subsequently amplified, filtered and recorded on a second channel of the Visicorder as shown in Figure 3.

The face mask had a DC flow resistance of $0.31 \text{ cm H}_2\text{O/L/sec}$ and a dead space volume of 0.71 L . The face mask was modified by simply reducing the amount of facial area in contact with the dead space volume. This modification was necessary as variations in the dead space volume, due to articulatory movements, resulted in spurious air flows. This sometimes caused difficulty in identifying the instant of closure and release on the air flow trace. In the modified mask, only the area around the mouth was in contact with the internal volume of the mask. This mouthpiece was made of contoured soft foam rubber painted with a thin layer of rubber calking compound and then covered with a thin coat of petroleum jelly. Thus, labial and mandibular movements were relatively unhampered while a good air tight seal was maintained. The internal area of the mask above the mouthpiece was fitted with a sloping plexiglass plate. The mask was firmly strapped in place and also hand held by the subject. These modifications of the face mask resulted in very good definition of the closure and release phase of the air flow trace. Photographs of the face mask appear in Figure 5.

A small microphone sealed into the face mask allowed recording of the acoustic signal on a third channel of the Visicorder. The subject and experimenter also monitored this signal over headsets to verify the accuracy of the speech samples. The acoustic signal was also used to drive an intensity meter which the subject used to maintain the same conversational loudness level for the production of each speech sample. Some typical air pressure and air flow traces are presented in Figure 6.

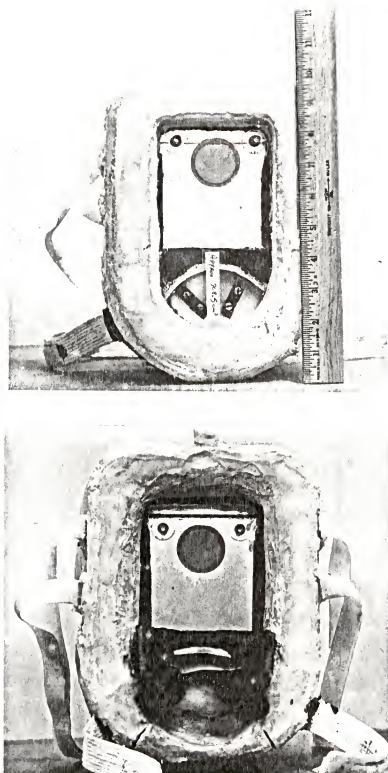


FIGURE 5. Photographs of the modified face mask and the oral catheter used for sensing air flow and supraglottal air pressure.

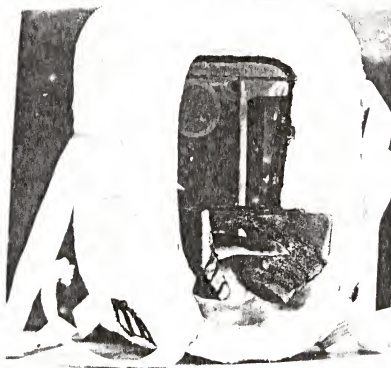


FIGURE 5-- continued

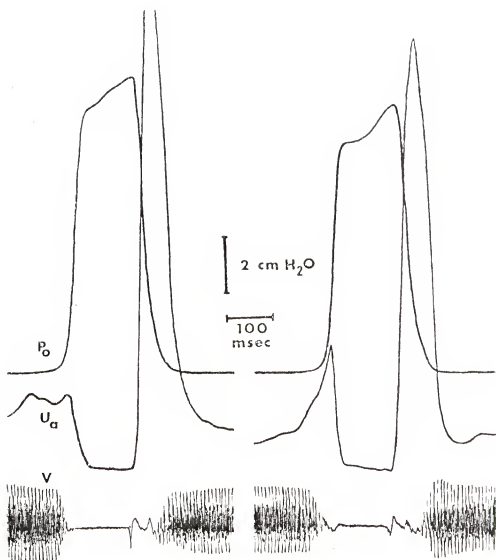


FIGURE 6a. Tracings of some typical simultaneous recordings of supraglottal air pressure (P_o), air flow (U_a) and the voice signal (V) during the production of voiceless stops.

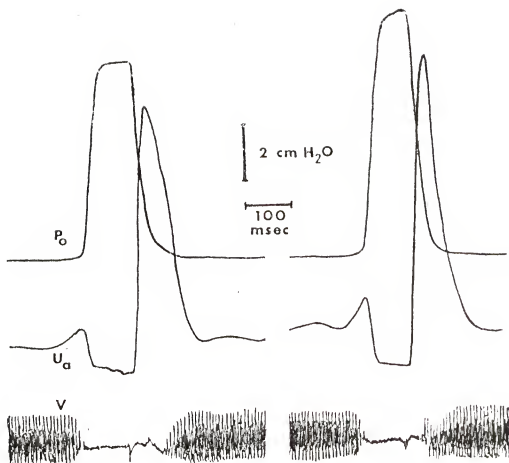


FIGURE 6a - continued

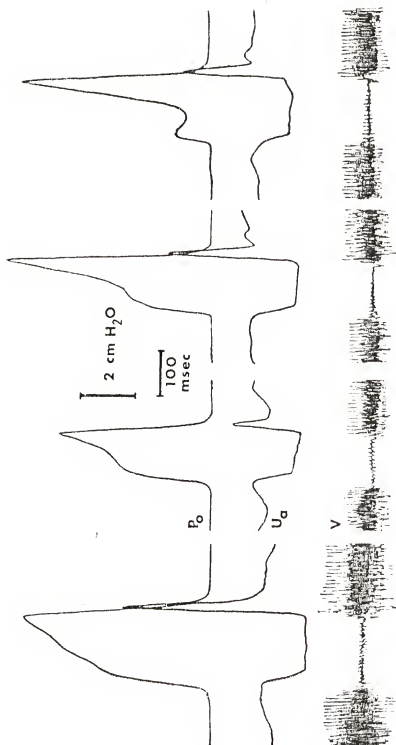


FIGURE 6b. Tracings of some typical simultaneous recordings of supraglottal air pressure, air flow and the voice signal during the production of voiced stops.

Measurement and Analysis

Volume velocity and supraglottal air pressure were graphically recorded at very high amplification and paper speed (6 inches per second) in an effort to reduce measurement error. Temporal measures were estimated to the nearest .001 second, and pressure to the nearest 0.05 cm H₂O.

The instant of complete articulatory closure, and the instant of release were identified on the volume velocity trace. As shown in Figure 7, perpendicular lines drawn from these points identified the instant of closure and release on the pressure trace. These points were then used as a physiological reference from which other points were measured on the pressure waveform.

Initially, the following points were measured on each pressure pulse (see Figure 7): T_c - Duration of the closing phase.

T_o - Duration of the occlusion phase.

T_r - Duration of the release phase.

P_c - Pressure at instant of closure.

P_k - Peak pressure.

P_r - Pressure at instant of release.

ΔT - Time between peak and release pressure.

Next, the area (A) under the pressure waveform bounded temporally by the point of closure and release, and in amplitude by the closure and release pressure was estimated by taking the mode of four separate polar planimeter (K & E Model 620005) measurements of each pressure pulse. These measurements were converted into the units cm H₂O·msec by determining the area of a rectangle of known pressure and time dimensions.

The average pressure above P_c during the occlusion phase, \bar{P}_o , was

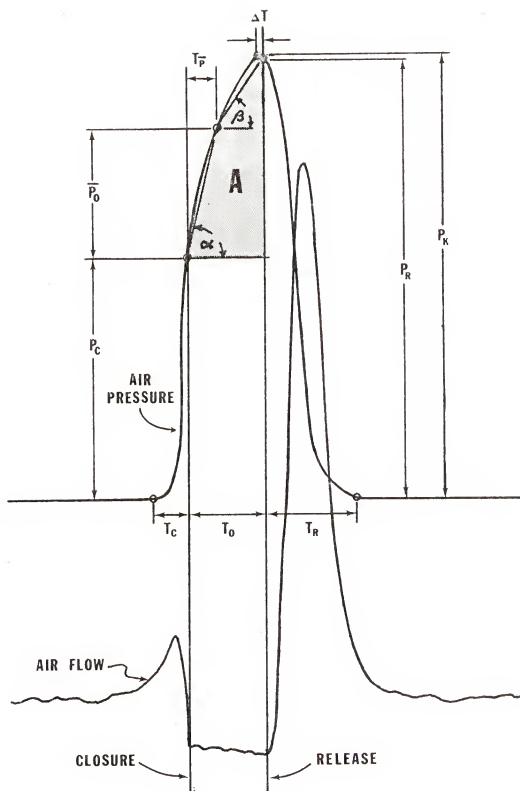


FIGURE 7. Graphic summary of the measurement scheme applied to each of the 240 pressure pulses analyzed in this study.

calculated by dividing the area by T_O . \bar{P}_O was then identified on the pressure trace and the time (T_P) between the instant of closure and \bar{P}_O was measured. The pressure impounded during the occlusion phase, XPCP, was calculated by subtracting P_c from P_r . The following calculations were then performed:

$$\alpha = \frac{\bar{P}_O}{T_P}, \quad \beta = \frac{XPCP - \bar{P}_O}{T_O - T_P}, \quad DIFF = \alpha - \beta$$

α and β are, therefore, the slopes of the two lines which are the statistically best fit approximation of the time course of the pressure during the occlusion phase. DIFF is an estimate of the waveform shape: $DIFF > 0$ indicates a convex waveform; $DIFF = 0$, linear; and $DIFF < 0$, concave.

Finally, some of the above measures were normalized so direct comparisons between the waveforms could be made. This was performed through the following calculations:

$$\alpha^* = (\alpha) \times (T_O/XPCP)$$

$$\beta^* = (\beta) \times (T_O/XPCP)$$

$$DIFF^* = \alpha^* - \beta^*$$

$$A^* = (A)/(T_O \times XPCP)$$

The data corpus described above was analyzed through a randomized-block factorial analysis of variance at an alpha level of 0.01. The treatments within this design were subjects, consonants, and vowels. Second and third order interactions, as well as main effects, were tested.

RESULTS

Qualitative Description of the Pressure Waveforms

After careful inspection of each of the 240 pressure traces, it was concluded that each pressure waveform had one of five general qualitative waveform shapes: convex, concave, linear, bimodal, or delayed. These categories refer to the shape of the waveform during the center portion of the pressure pulse. It was also found that each of the above categories could be further subdivided according to whether the initial portion of the pulse made a smooth or breaking transition into the central portion. Figure 8 displays each waveform type and its percentage of occurrence. Approximately half of the 240 pressure waveforms had a convex shape, while the remaining waveforms were primarily concave or linear; 60% exhibited a smooth transition while 40% showed a breaking transition. The breaking transition³ was usually coincident with a non-convex waveform (i.e., linear, concave, bimodal or delayed), and a smooth transition with a convex waveform.

Figure 9 displays the distribution of the above qualitative classifications as a function of consonant type and vowel environment. These results prompt the following generalizations:

1. No single consonant or vowel environment is unambiguously associated with a particular waveform shape or type of transition.

³Careful scrutiny of the pressure and air flow traces indicated that the region of the break in the pressure waveform closely corresponded to the instant of closure.

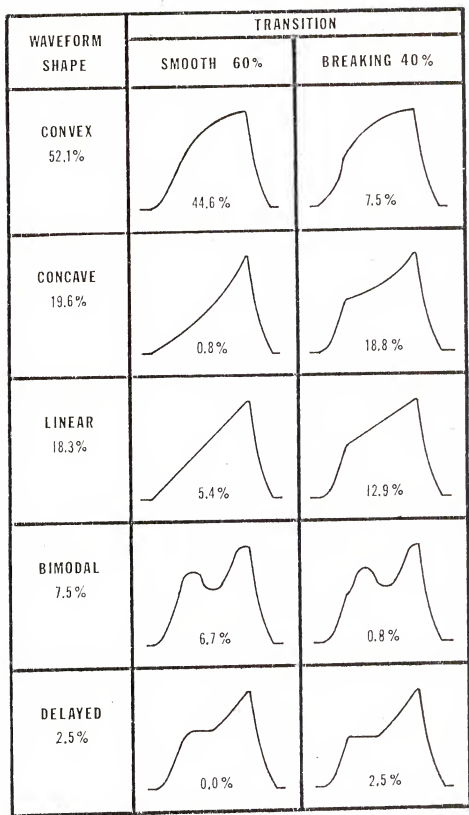


FIGURE 8. Stylized representation of each of the qualitative waveform shapes and their percentage of occurrence.

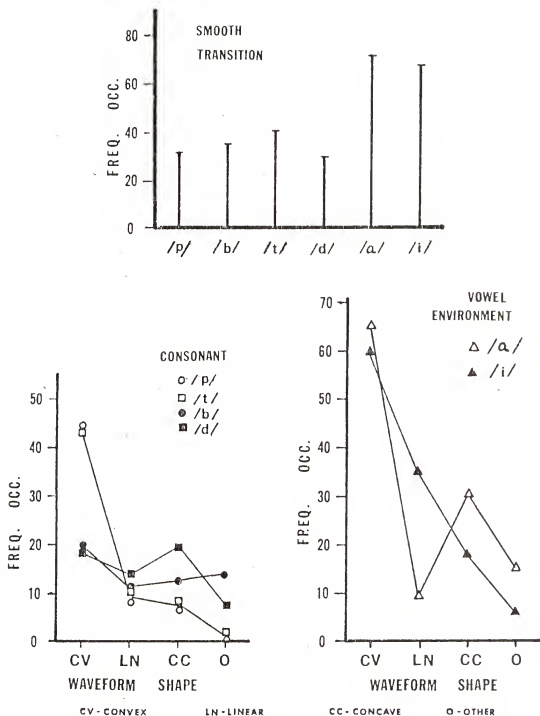


FIGURE 9. Frequency of occurrence of each of the qualitative waveform characteristics.

2. Voiceless stops are generally characterized by a simple convex waveform while voiced stops are usually nonconvex in appearance. In particular, approximately 70% of the voiceless stops exhibited a convex waveform, while 70% of the voiced stops were nonconvex in appearance.
3. The shape of the waveform transition (i.e., smooth or breaking) does not appear to be related to the consonant type of vowel environment.

Quantitative Description of the Pressure Waveforms

The average supraglottal pressure waveforms (as depicted by mean data points connected by straight lines) for each subject by VCV combination are presented in Figures 28 and 29 in the Appendix. In the statistical analysis these data were not averaged over subjects because the results of an initial analysis of variance (randomize-block factorial design, $\alpha = 0.01$) on the entire data set indicated that there was a significant subject effect on each of the measurands. This intersubject variability is apparent in the figures. In this initial study, however, only those effects which the subjects most often had in common are discussed. Consideration of the differential treatment affects as a function of the individual subjects in this study are reserved for a future report.

Tables 7 and 8 in the Appendix present the minimum set of measurands needed to describe each pressure waveform (i.e., $P_c, T_c, \alpha, XPCP, \beta, T_o$, and T_r) as well as four other summary measurands (P_k, A, TOT , and $DIFF$). The measurands P_r and ΔT are not included in either the table or figures because their occurrence and magnitude were small. In

76.7% of the 240 pressure traces measured, the peak pressure occurred at the instant of release (i.e., $P_k = P_r$). However, in the remaining 23.3% of the samples the peak either occurred after, or before the instant of release. Those peaks which occurred after the instant of closure showed an average increase in pressure above the release pressure of 0.18 cm H₂O (range, 0-0.63 cm H₂O) with the peak occurring an average of 6 msec (range, 2-18 msec) after the instant of release. This finding was relatively evenly distributed among the VCV sample types. Peaks which occurred before the instant of release had an average pressure of 0.24 cm H₂O (range 0.5-0.85 cm H₂O) above the release pressure, and occurred on the average of 18 msec (range, 8-27 msec) before the release. This event only occurred during some productions of /b/.

Two quantitative estimates of waveform shape during the occluded phase are DIFF* ($= \alpha^* - \beta^*$) and the normalized area (A^*). These data are presented in Table 9 of the Appendix. The calculated waveform is linear in shape when DIFF* = 0, convex when DIFF* > 0, and concave when DIFF* < 0. Similarly, $A^* = 0.500$ suggests a linear waveform, $A^* > 0.500$ convex, and $A^* < 0.500$ concave.

Analysis of the Effect of Manner, Place of Articulation and Vowel Environment

Initially, each of the fifteen dependent variables was analyzed by a randomized-block factorial analysis of variance ($\alpha=0.01$) with three treatment effects (subjects X consonants X vowels). The results of these fifteen analyses indicated that the subject main effect was significant for all measurands. This resulted in numerous three-way interactions and an extremely laborious post-hoc analysis. Therefore, the data were re-analyzed using the same design and alpha level, however,

each subject was analyzed separately for consonant and vowel effects. A total of seventy-five analysis of variance were performed (15 dependent variables X 5 subjects). The post-hoc analysis of significant F's were analyzed by Duncan's New Multiple Range Test at an alpha level of 0.01. These results were then collapsed and summarized using the planned comparison scheme shown in Table 1.

Analysis of the Manner Effect

Table 2 summarizes the results of the subject-wise post-hoc analysis of the effect of manner (i.e., voiced vs voiceless) on supraglottal air pressure. The results of the analysis display a good deal of inter-subject variability as well as two- and three-way interactions. It is possible, however, to make some generalizations across subjects. The closure (T_C) and occlusion duration (T_O) do not generally vary as a function of manner. They are approximately 50 msec and 100 msec in duration, respectively. However, the duration of the release phase (T_R) of voiceless stops was significantly longer than their homorganic cognates, 150 msec versus 80 msec, respectively. The total duration of the pressure pulse (TOTP) is greater for voiceless stops. However, this appears to be simply the result of systematic variation in the duration of the release phase (T_R). The pressure magnitude at the instant of closure (P_C) was characteristically higher for voiceless stops by approximately 1.5 cm H₂O. However, the additional increase in pressure above this point (XPCP) did not vary consistently. Generally the peak air pressure (P_K) of voiceless stops was either equal to, or greater than its cognate, and the area measure (A) was unaffected. As shown in Figure 10, voiceless stops displayed either a significantly faster pressure rise during the initial portion of the occlusion phase (α), or a

TABLE 1. Post hoc analysis scheme for the subject-wise paired comparison tests. Duncan's Test was applied to the entire VCV X VCV matrix. However, only those comparisons under the heading "THREE-WAY INTERACTION" were extracted. Where indicated by the results, these comparisons were then progressively collapsed according to the scheme outlined below.

TREATMENT UNDER TEST	TWO-WAY INTERACTION	THREE-WAY INTERACTION
Manner (Voiced vs Voiceless)	<p>/p/ vs /b/</p> <p>/t/ vs /d/</p> <p>(Place Interaction)</p>	<p>/apa/ vs /aba/</p> <p>/ipi/ vs /ibi/</p> <p>/ata/ vs /ada/</p> <p>/iti/ vs /idi/</p> <p>(Place X Vowel Interaction)</p>
Place (Bilabial vs Apical Alveolar)	<p>/p/ vs /t/</p> <p>/b/ vs /d/</p> <p>(Manner Interaction)</p>	<p>/apa/ vs /ata/</p> <p>/ipi/ vs /iti/</p> <p>/aba/ vs /ada/</p> <p>/ibi/ vs /idi/</p> <p>(Manner X Vowel Interaction)</p>
Vowel Environment (/a/ vs /i/)	<p>{/apa/ / ata/} vs {/ipi/ / iti/}</p> <p>{/aba/ / ada/} vs {/ibi/ / idi/}</p> <p>(Manner Interaction)</p>	<p>/apa/ vs /ipi/</p> <p>/aba/ vs /ibi/</p> <p>/ata/ vs /iti/</p> <p>/ada/ vs /idi/</p> <p>(Manner X Place Interaction)</p>

TABLE 2. Summary of the results of the subject-wise post-hoc analysis for the effect of manner of articulation. Significant main effects, as well as two- and three-way interactions are represented. For example, for the measurand TOT, subject #4 displays an interaction with place of articulation. That is, for the comparison /p/ vs /b/(p/b), /p/ had a significantly greater (>) TOT than /b/; however, for the apical alveolar comparison (t/d) no difference was found.

As an example of the manner in which three-way interactions are presented in this table, consider the t/d comparison for the measured TOT under subject #3: /t/ was significantly less than /d/ only when these two consonants were in the vowel environment /a/. A main effect is indicated when both comparisons (i.e., p/b and t/d) are significant and in the same direction.

TABLE 2

MEASUR-AND	SUBJECT XX AND COMPARISON									
	1		2		3		4		5	
	p/b	t/d	p/b	t/d	p/b	t/d	p/b	t/d	p/b	t/d
T_c					> α	> α				
T_0					>		<	< α		
T_r	>	>	>	>	>	>	> α	> α	>	>
TOTT	>	>	>	>	>	< α	>		>	>
P_c	>	>	> i	> i	>	> α	>	>	>	
α		>	>			> i	>	>	>	>
β	<	<	<	<	<	<			>	
DIFF	>	>			> i	> i		>	>	>
XPCP	<		<		> i < α		> i		>	
P_k		>	< α	>	>	>	> i	> i	>	>
A		> α			> i	> i			>	
α^*	>	>	>	>	> i	> i	>	>		
β^*	<	<	<	<		<	<	<		
DIFF *	>	>	>	>	> i	> i	>	>		
A *	>	>	>	>	> i	>	>	>	>	>

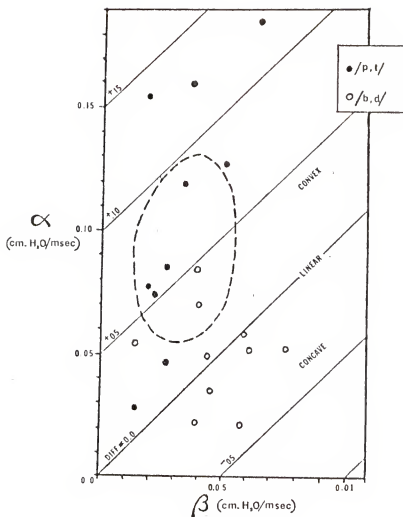


FIGURE 10. Plot of α versus β . The data points represent averages over vowel environments. Lines of equal DIFF (i.e., $\alpha - \beta$) are also plotted. The dashed ellipse is explained in a later section of the text.

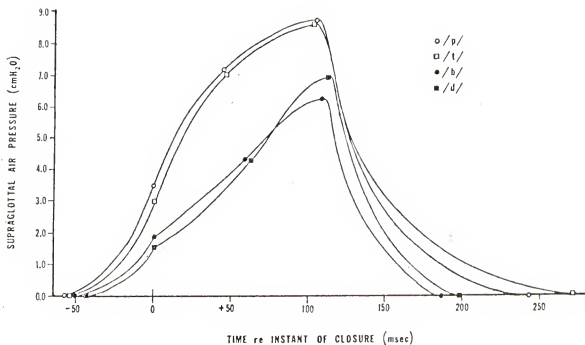


FIGURE 11. Coordinate plot of supraglottal air pressure versus time as a function of the consonants /p,b,t,d/. The coordinate data points have been averaged over subjects and vowel environments. The four waveforms have been temporally aligned so $t=0$ is the instant of closure on each waveform. The curved lines connecting data points are merely suggestive. The plotted points are: $0.0, -T_c$; $P_c + P_o$ (i.e., the intercept of α and β), T_p ; P_k , T_o ; and $0.0, T_o + T_r$.

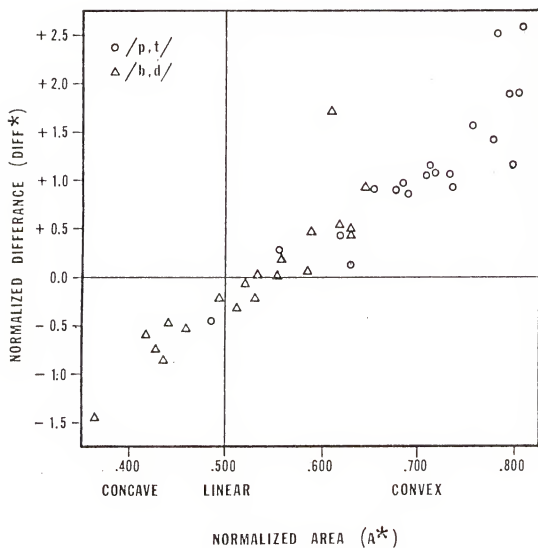


FIGURE 12. A plot of the normalized measurands $DIFF^*$ versus A^* as a function of voicing (i.e., /p,t/ vs /b,d/). Data points represent averages over vowel environment for each subject.

TABLE 3. Summary of the results of the subject-wise post-hoc analysis of the effect of place of articulation. See Table 2 legend for explanation of this type of tabular presentation.

MEASURE AND	SUBJECT VS AND COMPARISON									
	1		2		3		4		5	
	p/t	b/d	p/t	b/d	p/t	b/d	p/t	b/d	p/t	b/d
T_c	>a	>a			>a	>a				
T_o	>i				>		>i			
T_r		<	<		<i	<i				
TOTT			<	<						
P_c			<i							
α	<		>		<i		<		>	
β		<			<					<
DIFF			>		<i					
XPCP	<		>		<i		<a		>	
P_k	<		>a	<a			<a		>	
A										
α^*			>							
β^*			<							
DIFF*			>							
A*				<a						

TABLE 4. Summary of the results of the subject-wise post-hoc analysis of the effect of vowel environment. See Table 2 for explanation of this type of tabular presentation.

MEASUR-AND	SUBJECT \times AND COMPARISON				
	1	2	3	4	5
	a/i	a/i	a/i	a/i	a/i
T_c	< t	<	< d		<
T_0	> t	<	>	> d	
T_r			< $\begin{smallmatrix} t \\ d \end{smallmatrix}$	< d	<
TOTT	<	<	< $\begin{smallmatrix} t \\ d \end{smallmatrix}$		<
P_c		< $\begin{smallmatrix} p \\ t \end{smallmatrix}$	> $\begin{smallmatrix} p \\ t \end{smallmatrix}$		
α			< $\begin{smallmatrix} p \\ t \end{smallmatrix}$		
β				<	
DIFF	<	>	< $\begin{smallmatrix} p \\ t \end{smallmatrix}$		
XPCP			< $\begin{smallmatrix} p \\ t \end{smallmatrix}$	< p	
P_k		> t		< p	
A					
α^*			< $\begin{smallmatrix} p \\ t \end{smallmatrix}$		
β^*			>		
DIFF *			< $\begin{smallmatrix} p \\ t \end{smallmatrix}$		
A *			< $\begin{smallmatrix} p \\ t \end{smallmatrix}$		

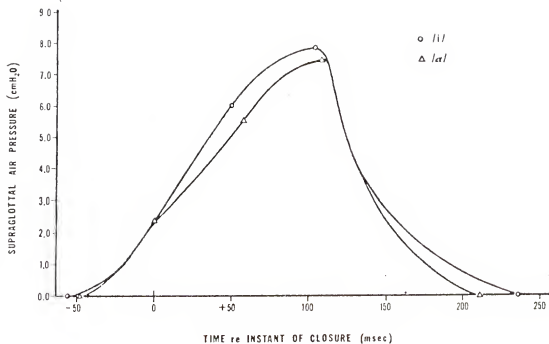


FIGURE 13. Coordinate plot of supraglottal air pressure versus time as a function of vowel environment. The data points are averaged over subjects and consonants. See legend of Figure 11 for further description of this type of graphic presentation.

slower rise during the remainder of this phase (β). Figure 11 graphically summarizes these general findings.

The normalized measures (α^* , β^* , DIFF^* , A^*) indicated that the shape of the pressure waveform of voiceless stops was usually more convex (or less concave). These data are graphically presented in a plot of DIFF^* versus A^* in Figure 12.

Analysis of the Place Effect

A summary of the results of the post-hoc analysis of the effect of place of articulation (i.e., bilabial vs apical alveolar) appears in Table 3. Although there is a good deal of intersubject variability and some two- and three-way interactions, these findings support the conclusion that there is generally no single measurand that displays a somewhat consistent variation across subjects. However, for each subject one can usually find at least one measurand which varied significantly.

Analysis of the Vowel Effect

A summary of the results of the post-hoc analysis of the effect of vowel environment (i.e., /**a**/ vs /i/) on the pressure pulse of the embedded consonant is presented in Table 4. One again finds a good deal of intersubject variability and consonant interaction. It is possible, however, to draw some rough conclusions (see Figure 13):

- Voiceless stops were more affected by vowel environment than voiced stops.
- Generally, the vowel environment only affected the temporal measurands. Consonants in the presence of /**a**/ had shorter closing and release durations while the effect on T_0 was mixed. There is some evidence for an inverse relationship between T_c

and T_0 (see Subject 1 and 3 in Table 4). The overall effect of the vowel environment /a/ on the consonant pressure pulse, as summarized by TOT, was to make it shorter than /i/.

Summary of Results

1. There was a considerable amount of intersubject variability in the data. This variability was not only in the average magnitude of each measurand, but also in the degree and direction to which they were affected by the various experimental treatments (i.e., manner and place of articulation, and vowel environment). Generally, for each subject at least one measurand was significantly affected by each treatment. The affected measurand, however, was not always the same across subjects.
2. During the occluded portion of stop consonants, the pressure waveform generally had either a convex, linear, or concave shape. While a particular waveform shape was not unambiguously associated with a particular consonant, it was found that voiceless consonants most often had a convex appearance and voiced consonants a nonconvex appearance.
3. On the basis of quantitative estimates of waveform shape it was found that even in instances where qualitatively similar waveforms are observed, voiceless stops were generally more convex (or conversely, less concave).
4. More than half of the pressure waveforms showed a smooth transition during the instant of articulatory closure. The remaining waveforms exhibited a breaking transition. Waveforms with a concave or linear waveform most often exhibited a break-

ing transition.

5. Complete articulatory closure occurred at about 50 msec after the onset of the registration of supraglottal air pressure. Peak pressure usually occurred at or about 5 msec after the instant of articulatory release.
6. The duration of the closing and occluded phase of the pressure pulse was not generally affected by manner or place of articulation. However, the duration of the release phase was significantly longer for voiceless stops.
7. The air pressure magnitude of voiceless stops at the instant of closure was roughly 1.5 cm H₂O higher than voiced stops.
8. During the occluded phase, voiceless stops (as compared to their homorganic cognates) had either a faster pressure rise during the initial portion of this phase, or a slower rate during the final portion.
9. The peak supraglottal air pressure of voiced stops was either less than or equal to their homorganic cognates.
10. Place of articulation did not appear to affect supraglottal air pressure.
11. Vowel environment affected voiceless stops more than voiced stops. Generally, only the temporal measurands were affected.

DISCUSSION

Introduction

The discussion which follows attempts to establish the relationship between the various measurands examined in this study and certain aspects of consonant articulation. This in turn leads to an articulatory interpretation of the significant treatment effects.

The discussion proceeds by first considering the principle temporal measures (T_c , T_o , and T_r). Next, an interpretation of the amplitude and waveform measurands is presented with the aid of a computer simulated model of VCV production.

The Principle Temporal Measurands

Closure Duration

The duration of the closing phase (T_c) of stop consonants produced in VCV utterances was defined as the time between the initial registration of P_o and the instant of zero air flow (i.e., complete closure at the consonantal point of articulation). During the closing phase the cross-sectional area at the point of articulation (A_a) is decreasing rapidly; consequently, the flow resistance at this point quickly approaches infinity. Thus, T_c is primarily a reflection of the VC transition time of A_a . A few additional comments must be added, however.

The instant at which air flow subsides clearly denotes the end of the closing phase. However, several factors influence the denotation of the beginning of this phase (i.e., the registration of P_o).

During the VC transition, A_a is decreasing from 2-5 cm^2 to zero in about 100 msec (Fant, 1960, p. 115; Öhman, 1965; Kent and Moll, 1969). During the initial portion of the transition A_a is very large and the resulting increase in P_o is extremely small. Therefore, it is important to note that the instant of P_o registration above baseline is greatly affected by the sensitivity of the pressure sensing instrumentation. With the instrumentation used in this study it was possible to discern changes in the order of 0.02 to 0.05 $\text{cm H}_2\text{O}$ above the baseline P_o . A rough estimate⁴ of the corresponding A_a needed to cause a registration of this magnitude is 0.4-0.5 cm^2 . Thus, only when A_a becomes as small as this critical area (A_c) will P_o begin to register on the recording device. Therefore, the T_c measures reported here do not reflect the entire A_a transition; they reflect that portion of the transition from $A_a = A_c$ to $A_a = 0$.

An additional factor which must be considered is the nature and stability of the baseline from which the initial registration of P_o is referenced. During the steady-state pre-consonantal vocalic portion of the VCV the P_o is extremely small and primarily determined by the most constricted part of the vocal tract down stream from the point where the pressure is measured. For the vowels under study, the minimum cross-sectional area (A_v) is about 0.65 cm^2 (Fant, 1960, p. 115) to 0.30 cm^2 (Stevens, 1971). If A_v is less than A_c slight variations in A_v due to mandibular co-articulation may cause some slight baseline variability. Other factors that may cause minor fluctuations in the baseline P_o are the magnitude and rate of change of glottal resistance

⁴This estimate is based upon the performance of the computer simulated model of VCV production presented in a subsequent section of this discussion.

and active supraglottal cavity enlargement, and, to a lesser extent, the impedance of the walls of the supraglottal cavity. However, the results of this study indicate that the influence of these factors is probably very small. As it is generally agreed that the magnitude and/or presence of these factors is dependent upon whether the stop is voiced or voiceless⁵, significant variations in T_c as a function of manner might be expected. However, these were not found and it may be concluded that such influences on the initial registration of P_o are small. This leads to the conclusion, as summarized in Figure 14, that T_c primarily represents the transition time of A_a from $A_a = A_c$ to $A_a = 0$ (where $A_c = A_v$) and that A_c is a relatively stable region. With this understanding of the nature of T_c a closer look may be taken at the way it is influenced by the various treatments in this study.

Based on the lateral cineradiographic studies of Perkell (1969) and Kent and Moll (1969, 1972) one would expect the consonantal point of articulation (whether at the lips or tongue) to take about 10-20 msec to close an area of 0.5 cm^2 (i.e., A_c). These predicted durations are smaller than the T_c 's found in this study (40-50 msec). As the total VC transition time of A_a is about 100 msec, these data indicate that A_a is less than A_c during nearly half of the total transition. It seems probable that the inflated T_c values reflect the influence of the face mask upon articulation. The mouthpiece of the face mask used in this study tends to compress the upper lip and thereby lower it slightly. The mouthpiece also affects the normal mandible carriage by causing it to articulate about a more elevated position. Similar face mask ef-

⁵Details concerning this general statement are given in subsequent sections of this discussion.

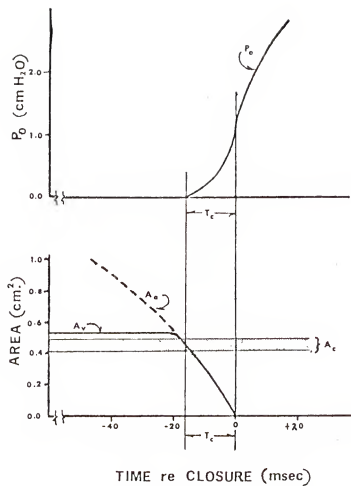


FIGURE 14. Stylized drawing depicting the articulatory interpretation of the measurand T_c . See text for explanation of this figure.

fects have been reported by Lubker and Moll (1965). As shown in Figure 15, the combination of these affects would cause an overall reduction in A_a (and perhaps A_v)⁶ and cause it to pass through A_c sooner, and thus increase T_c . Although it appears that the face mask affected articulation slightly, this is an experimental constant and should not alter the validity of the treatment effects reported below.

The experimental treatment which most affected T_c was vowel environment. Consonants in the /a/ environment generally had a significantly shorter T_c than in the /i/ environment (45 msec and 55 msec, respectively). Kent and Moll (1969) reported that although the closure duration for the entire VC transition does not appear to be vowel dependent, the rate of closure does. They report significantly faster A_a closure rates for /a/ as opposed to /i/, due to the fact that A_a begins its transition from a more open vocalic position. This difference in rate would account for the significant vowel treatment affect.

In a manner similar to that shown in Figure 15, this difference in rate would cause A_a to transcend A_c at different points in time and the T_c measures would reflect this difference in rate⁷. Therefore, these results support Kent and Moll's conclusion that rate of closure of A_a varies directly with the openness of the preconsonantal vowel.

⁶Very slight differences (less than about 0.2 cm H₂O) between the pre- and postconsonantal P_o baselines were sometimes found for stops produced in the /i/ environment. Generally, such shifts were not found for consonants in the /a/ environments. Such baseline shifts may be explained by slight variations in A_v . The fact that such shifts were not generally found for /aCa/ is simply explained by noting that the pressure sensing catheter is positioned down stream from A_v .

⁷It is interesting to note that in the few instances where T_c was found to vary as a function of place and manner, such effects only occurred when consonants were in the /a/ environment. A possible explanation is that because A_a crosses the region A_c at a faster rate, the measure of T_c is subject to less variability and significant differences are more easily discerned.

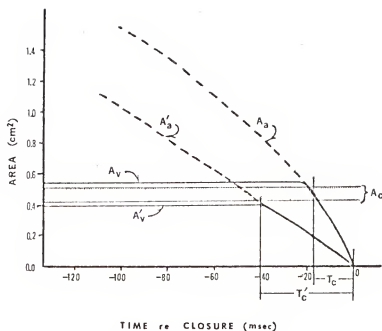


FIGURE 15. The effect of the face mask on the measurand T_C . Superscripted symbols represent articulation with the face mask in place. See text for further explanation of this figure.

It was also found in this study that T_c was generally not affected by variations in manner or place of articulation. To the extent to which T_c reflects the A_a transition, these data support Kent and Moll's conclusion that the A_a transition during the VC portion of isolated VCV's appears to be independent of the manner in which homorganic stops are produced.

Occlusion Duration

The occlusion duration, T_o , was defined as the length of time during which the air flow at the point of consonantal articulation was zero. Stated in articulatory terms, this represents the time during which $A_a = 0$. This duration, like T_c , was remarkably stable regardless of place or manner. Similar T_o durations of about 100 msec have been reported by Öhman (1965) and Kent and Moll (1969).

Both the T_c and T_o data lend support to Kent and Moll's conclusion that it may not be possible to differentiate homorganic stops on the basis of the dynamic changes at the articulatory constriction. The T_c and T_o data in this study (to the extent to which they reflect A_a) also suggest that nonhomorganic stops (specifically bilabials and apical alveolars) have very similar articulatory gestures.

Release Duration

The release duration (T_r) was defined as the time between onset of air flow and the return of P_o to baseline. The analysis to T_r resulted in one of the most consistent findings in this study; viz., voiceless stops have longer T_r 's than voiced stops.

Kent and Moll (1972) reported that the rate of the release gesture is slightly less than the closing gesture. If it is assumed that the

effect of the face mask on the release gesture is about the same as it was on the closing gesture, T_r 's in the range of 60-70 msec would be expected. The T_r data for the voiced consonants /b/ and /d/ fall within this range. However, Kent and Moll also reported that homorganic stops were produced with the same release gesture. Therefore, if T_r is simply a reflection of the A_a transition during the release phase, /p,t/ should have the same T_r as /b,d/, respectively. The data indicate however, that the T_r for voiceless stops is about 65 msec longer than their homorganic voiceless cognates. Therefore, if it is assumed that homorganic stops do indeed have similar release gestures, then it must be concluded that other factors (besides A_a) tend to maintain an elevated P_o during the release phase and thus influence the T_r measurand.

Fant (1960, p. 279) and Stevens (1956) cite the following factors as important in determining T_r :

1. The magnitude of P_o at the instant of release (P_r) - i.e., given equal decay rates, T_r varies as P_r .
2. The rate of area increase at the point of articulation - i.e., T_r is inversely proportional to the rate of increase in A_a . It should be noted that this relationship is complicated due to the nonlinear relationship between A_a and the flow resistance (R_a) this orifice creates. During the release phase of stops, the air flow is relatively large (Isshiki and Ringel, 1964). Under such conditions R_a is also proportional to the air flow. Therefore, the elevation of P_o during the release phase is dependent on both the air flow through A_a and its dimensions.
3. The volume of air compressed within the subglottal and supraglottal cavities and the degree to which these cavities are

coupled to each other (via the resistance at the glottis) and with the outside atmosphere (via R_a). These factors influence the time constant of the decay rate of P_o .

4. The possibility of a superimposed expiratory breath-pulse.

Therefore, even though the T_r data for /b/ and /d/ fall within the expected range based upon the transition rate of A_a , the possible influence of the above factors complicate an interpretation of T_r based upon A_a . Moreover, if it is assumed that homorganic stops have the same A_a transitions, the significantly longer T_r 's found for voiceless stops demonstrates the degree to which the above factors influence T_r .

The articulatory interpretation of the T_r data is further complicated by the fact that the factors above must be controlled by the speaker in order to affect a voice onset time and aspiration level appropriate for the particular consonant. Therefore, variations in T_r may not be interpreted simply in terms of the physical characteristics of the speech production system alone.

Further insight into the articulatory interpretation of the T_r data can be achieved by evaluating the relative influence of the factors listed above in connection with other findings in this study. The discussion will again focus upon T_r in a later section.

Amplitude and Waveform Characteristics

Articulatory Considerations

Particular attention will focus on articulatory comparisons as a function of manner as this treatment resulted in the most consistent and significant changes in P_o magnitude and waveform. This finding suggests that the P_o waveform is intrinsically associated with the articulatory

mechanisms which facilitate the voicing and devoicing of stops.

One of the central questions in the study of stop consonant production is how voicing continues when the vocal tract is occluded. As discussed by Rothenberg (1968), there appear to be several parallel mechanisms which may act independently or collectively to facilitate voicing or devoicing. Basically, these mechanisms are of two types: glottal and supraglottal articulatory adjustments (e.g., increases in average glottal area and pharyngeal cavity expansion) which may either sustain or diminish the aerodynamic driving force which maintains vocal fold vibration; and internal laryngeal adjustments (e.g., changes in vocal fold tension) affecting the physical characteristics of the folds and thereby their mode and frequency of vibration as well as their susceptibility to oscillation. This implies that there are several possible voicing/devoicing strategies (i.e., unique combinations of coarticulating gestures), and that the particular strategy used by a speaker is probably dependent on the phonetic and prosodic environment of the stop. With regard to this study, if it is assumed that the P_0 waveform is indeed a sensitive reflection of the aerodynamic consequence of the particular voicing/devoicing strategy employed, one might expect that because isolated VCV's are relatively unconstrained a variety of mechanisms may be utilized, and thus, an assortment of waveforms produced. It might be further speculated that analysis of the differences in amplitude and waveforms compared both homorganically and nonhomorganically, may yield information regarding the various mechanisms that facilitate voicing and devoicing.

* Presently, little is understood regarding the nature of internal

laryngeal adjustments⁸ during stop production. However, a number of studies have investigated the glottal and supraglottal adjustments that occur during the production of these consonants. These studies report that intervocalic voiced stops are characterized by:

- a. A relatively constant glottal area throughout the duration of the consonant -- or a slight increase in area during the middle of the occlusion phase (Sawashima, 1970).
- b. A lower impedance of the supraglottal cavity walls (Rothenberg, 1968).
- c. Active volumetric expansion of the supraglottal cavity (Bell-Berti and Hirose, 1972).

Intervocalic voiceless stops are characterized by:

- a. Varying degrees of glottal adjustment. For voiceless unaspirated stops (as in this study) the average glottal area remains relatively constant or increases slightly. The area increase may begin before or after the instant of consonantal closure and the decrease begins just after the release of the stop. Aspirated stops have a larger area adjustment and the glottis remains open for a longer period of time after the consonantal release (Kim, 1970; Sawashima, 1970; Dixit and MacNeilage, 1974).
- b. The impedance of the walls of the supraglottal vocal tract is higher (Rothenberg, 1968).
- c. An expiratory breath pulse is sometimes associated with voiceless stop production at slow syllabic rates (Cooker, 1963).

⁸Theoretical discussion of this topic can be found in Halle and Stevens (1971) and Mermelstein (1971).

Simulation of a Model of VCV Production

The complex relationship between the physiological variables listed above and their effect on the time-course of P_o has been summarized in a model proposed by Rothenberg (1968)⁹. The electrical circuit analogy of Rothenberg's model¹⁰ is presented in Figure 16. The elements comprising the model are the following:

E_t - Net effective respiratory muscle innervation.

Z_t - Net effective respiratory tissue impedance.

Z_s - Volume and flow resistance of the lungs and trachea.

R_g - Average glottal resistance calculated (in cgs units) according to the general equation given by van den Berg et al (1957):

$$R_g = \frac{12\mu d l^2}{A_g^3} + \frac{0.44\rho |U_g|}{A_g^2};$$

where μ = Kinematic viscosity of air,

d = Vocal fold thickness (0.3 cm),

l = Fold length (1.8 cm),

A_g = Area of the glottal orifice,

ρ = Density of air,

and U_g = Volume velocity through the glottal orifice.

⁹A lucid explanation of the development of this model and its underlying assumptions can be found in Rothenberg's 1968 monograph (see bibliography).

¹⁰Some of the elements in the present model are slightly different than originally proposed by Rothenberg. The volume of air in the supra-glottal cavity is 70 ml rather than 40 ml (see Fant, 1960, p. 279). The possible shunting effect of incomplete velar pharyngeal closure has been omitted as a recent study concluded that there was negligible nasal air flow during (unnasalized) VCV's (Lubker, 1973); and the flow resistance at the point of articulation and at the glottis is modeled as a nonlinear (rather than linear) resistance.

I_e - Net effective air flow resulting from muscularly activated volumetric changes in the supraglottal cavity.

C_o - Compliance of the air within the supraglottal cavity.

Z_w - Impedance of the walls of the supraglottal cavity. (See Table 6 for LCR values).

R_a - Flow resistance at the point of articulation calculated by the equation (cgs units):

$$R_a = \frac{12\mu D L^2}{A_a^3} + \frac{0.44\rho |U_a|}{A_a^2};$$

where D = Thickness of the orifice at the point of articulation (0.8 cm),

L = Lateral length of the orifice (2.0 cm),

A_a = Area of the orifice at the point of articulation,

and U_a = Volume velocity through the orifice.

As an aid to the articulatory interpretation of the findings in this study, Rothenberg's model was simulated on an IBM 370/165 digital computer using the IBM Continuous System Modeling Program (CSMP). The parameter settings used in the simulations were based on a) the results of the studies listed above, b) cineradiographic data reported by Perkell (1969) and Kent and Moll (1969, 1972), c) estimates of vocal tract wall impedance collected by Rothenberg (1968) and Ishizaka et al. (1974), d) theoretical arguments presented by Halle and Stevens (1967) and Rothenberg (1968), and e) an A_a transition-time (i.e., T_c , T_o , and T_r) estimated from the results of this study. The initial conditions and parameter settings for each simulation are indexed in Table 5. The detailed results of two typical simulations are presented in Figures 17 and 18. Although the predicted air pressure and air

flow variations (as shown in these figures) are quite reasonable¹¹, it should be emphasized that the model primarily serves a heuristic and demonstrative purpose. Use of the model as a deductive research tool is rather limited at this time. Of particular import is the fact that quantitative information concerning internal laryngeal adjustments and the time-course of $A_g(t)$, $I_e(t)$ and $E_t(t)$ are presently unavailable. Although these parameters were modelled with reasonable timing and magnitude estimates, much more precise information is necessary. Indeed, when such information is available and incorporated, at least one test of the validity of the model will be its ability to predict and explain the qualitative and quantitative pressure data collected in this study.

Articulatory Interpretation of the Pressure and Waveform Data

The Effect of Changes in Wall Impedance

As shown in Figure 19, increasing wall impedance (Z_w) causes P_c , P_k and α to increase; the effect on T_c , T_r , and β is relatively small. Decreasing Z_w has similar effects but in the opposite direction. A partial explanation therefore, of the difference between voiced and voiceless stops on the measurands P_c , P_k , and α may be explained by differences in Z_w . However, the range of Z_w 's (tense to relaxed walls) represents extremes probably not encountered in actual VCV production. Therefore, it seems more likely that changes in Z_w may only explain differences in P_k of about 1.0 cm H₂O, differences in α of about 0.025 cm H₂O/msec and differences of 0.5 cm H₂O in P_c . The differences found in

¹¹In the simulations detailed in Figures 17 and 18 the peak oral air flow during the release of the stop is smaller than expected due to the exaggerated release duration (T_r) of A_a . Shorter release durations (15-25 msec) produce peak air flows comparable with those found by Isshiki and Ringel (1964).

this study were generally larger. Thus, while changes in Z_w may contribute to such differences, the data indicate that other factors are probably more influential.

This conclusion is also supported by the α and β data. A rough estimate (based on the simulations) of the range of values of α and β for tense and relaxed walls and slight variations in subglottal pressure (7-9 cm H₂O) and occlusion duration (75-125 msec) is denoted by the dashed ellipse in Figure 10. Most of the data points (for both voiced and voiceless stops) fall outside of the range¹². It may be concluded, therefore, while differences in Z_w may contribute to changes in α and P_k , its influence is relatively small compared to the other factors considered below.

Glottal Adjustments

Figure 20 shows the effect on P_o of various glottal adjustments. The gross timing and magnitude of these adjustments are appropriate for voiceless stop production based on the articulatory considerations reviewed above. Such adjustments have a considerable effect on α and β and T_r . As shown in the figure, if the walls of the vocal tract are tense (as in these simulations) a glottal adjustment has very little effect on the pressure at the release of the stop. However, if the walls are less tense, a glottal adjustment will cause a more elevated P_k (see Figure 21).

¹²It might be speculated that those data points (for both voiced and voiceless stops) that do fall within range were produced with a relatively small amount of glottal adjustment and/or cavity expansion and that the voicing/devoicing mechanism used in these productions employed relatively equal contributions of these factors and wall impedance.

Regardless of the wall impedance, the closure pressure (P_c) may be elevated considerably if the glottal adjustment begins during the closing phase (simulations 4 and 18 in the figures). Many of the air flow traces in this study showed a sudden increase in flow during the closing phase of voiceless stops. This suggests that the glottis is beginning to open during the closing phase. Therefore, at least one of the reasons why voiceless stops have a greater P_c than voiced stops is the difference in glottal adjustment between the cognates.

The simulations shown in Figure 20 also demonstrate the inter-relationship between P_c and α and β . If the glottal adjustment occurs at, or after the instant of consonantal closure there results a marked increase in α and decrease in β . However, if the adjustment occurs before the instant of closure, P_c becomes more elevated and causes a considerable reduction in the calculated value of α . This would explain the relatively wide range of α -values associated with voiceless stops. It might be speculated that the voiceless stops shown in Figure 10 having α 's less than 0.06 cm H₂O/msec were produced with an adjustment that began before closure; voiceless stops with midrange α 's were apparently produced with no glottal adjustment, or a slight postclosure adjustment; and stops with α 's greater than 0.12 cm H₂O/msec were produced with a postclosure adjustment.

The effect of a glottal adjustment appropriate for voiced consonants is shown in Figure 22. The gross timing and magnitude of these adjustments was based on the articulatory considerations reviewed above. As demonstrated by the simulations, when a voicing adjustment of this type is used, it causes α and P_k to increase. This would explain why voiced and voiceless stops sometimes did not have significantly differ-

ent α 's and/or P_k 's. Moreover, it may indicate that some subjects use the following voicing/devoicing strategy: tense walls and no glottal adjustment for devoicing; lax walls and glottal adjustment to sustain voicing.¹³

The general shape of the P_0 waveform for stops produced with and without glottal adjustment is generally convex. Articulatory mechanisms which produce more complex waveforms (e.g., concave, bimodal, etc.) are discussed below.

Active Supraglottal Cavity Enlargement

The effect of muscularly activated cavity expansion (I_e) on P_0 is shown in Figures 23 and 24 (expansion with moderate wall impedance) and Figure 25 (relaxed wall impedance). Unlike the effect of increased wall impedance and glottal adjustment, which generally makes the P_0 waveform more convex in appearance, I_e causes the waveform to become more linear or concave, decreases P_k and α , and increases β . Moreover, if the expansion begins during the closing phase, P_c will also be reduced. The effect of I_e offers another articulatory explanation of why congenates differ on these measurands. In addition, it explains why most voiced stops have concave or linear waveforms.

The voiced stops in Figure 10 with DIFF's less than or equal to zero probably represents stops in which voicing was continued via I_e rather than a glottal adjustment. The latter is contra-indicated as this would cause a more convex waveform (see simulations 12 and 13 in

¹³The use of active cavity expansion (I_e) to sustain voicing is contra-indicated as this would tend to maximize differences between the cognates on the measurand α (and possibly P_k).

Figure 22). It might be speculated further, that voiced stops with DIFF's greater than zero are produced with the following mechanism (in order of increasing α): a) lax walls, no glottal adjustment and I_e ; b) a glottal adjustment and cavity expansion; and c) a glottal adjustment only. It is interesting to note that bimodal waveforms¹⁴ (which were only found for voiced stops) may be produced when the timing of the glottal adjustment and I_e is asynchronous (see Figure 26). It is not clear, however, whether this represents a) an unintentional asynchrony of gestures, b) an abrupt change in voicing strategy, or c) a separate strategy in itself.

Expiratory Breath Pulse

The fact that this mechanism is present during the production of voiceless stops is suggested by the following:

1. Voiceless stops had significantly longer T_r 's than voiced stops. Using reasonable parameter settings it is not possible to simulate a voiceless consonant with a T_r as large as 150 msec without imposing an expiratory breath pulse (E_t).
2. The peak volume velocity at the lips during the release of voiceless stops was often much higher than anticipated. Based on the assumption that homorganic stops have similar A_a release gestures, and that the opening rate of A_a is reduced due to the effect of the face mask, this additional resistance

¹⁴Bimodal waveforms will also be produced if the closure rate of A_a is faster than the dynamic response of the cavity walls. Such rates (in excess of .05 cm²/msec), though possible in normal speech, were probably not possible in this study due to the effect of the face mask on articulation. The interrelationship between closure rate and the dynamic characteristics of the glottal and supraglottal structures would appear to be the primary determinate of whether a waveform will have a breaking or smooth transition.

(R_a) should greatly reduce the peak flow rate during the release (peaks in the range of 0.4-0.5 L/sec are predicted by the simulations (see Figure 17). However, peak volume velocities within the range normally expected for voiceless stops (0.8-1.1 L/sec), were often produced.

3. The concave waveforms found for some voiceless stops indicates that either an active volumetric cavity reduction was initiated just prior to release of the stop, or more likely, that an expiratory breath pulse was initiated before the release.¹⁵

Simulations demonstrating the effect of E_t are shown in Figure 27. The effect of E_t on P_o probably accounts for the concave waveforms and the more extreme P_k 's sometimes found for voiceless stops. The effect, of course, is primarily dependent upon the timing of E_t relative to the events at the consonantal constriction. Based on the T_c data, it seems reasonable to assume that an expiratory breath pulse was nearly always used during voiceless stop production and, since extreme P_k 's and concave waveforms are less generally found, that the breath pulse is timed so that it is maximally effective just after the consonantal release.

¹⁵The finding that P_o sometimes continues to increase for a very short time (about 6 msec) after the release also suggests the presence of an expiratory breath pulse or an active cavity contraction (i.e., negative I_e).

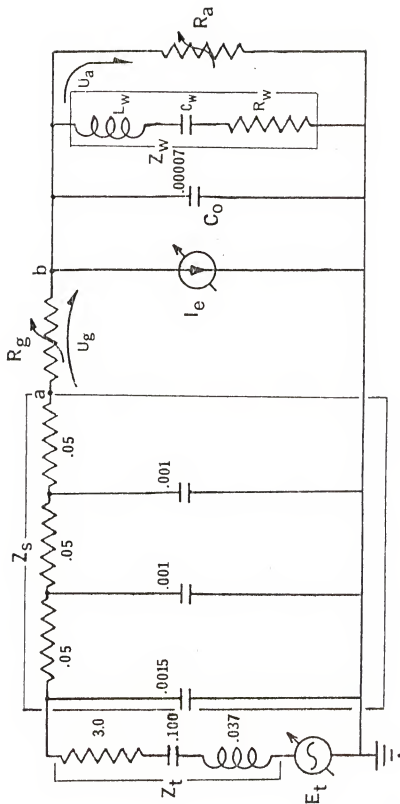
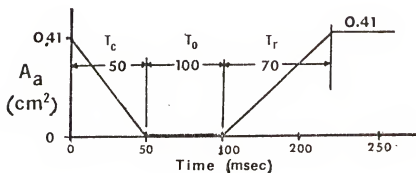
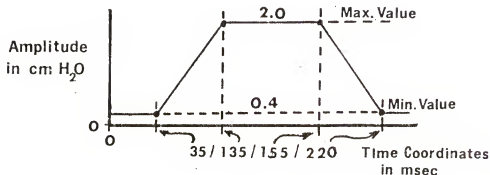


FIGURE 16. Circuit analogy of the model adapted from Rothenberg (1968) for the simulation of VCV's. Subglottal and supraglottal air pressure correspond to the node voltages at points a and b, respectively. The values of all circuit elements are in units derived from the measurement system cm H₂O/liters/seconds.

TABLE 5. Index of Simulations. The parameter settings for each of the twenty-one simulations is shown in the table. All simulations had the same initial conditions (a steady state solution for a subglottal pressure of 8 cm H₂O) and the same area function at the consonantal point of articulation as shown below.



The LCR values corresponding to each of the three levels of wall impedance are presented in Table 6. The glottal adjustment and expiratory breath pulse were modelled by using ramp functions. The manner in which the time course of these functions are reported in the table, is shown below.



Supraglottal cavity expansion was modelled as a sinusoidal current source. The characteristics of this current source are reported in the table as shown below.

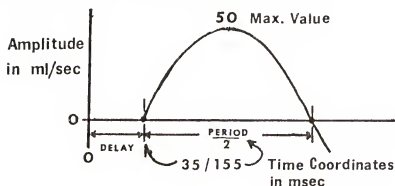


TABLE 5 - continued

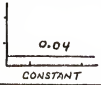
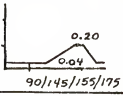
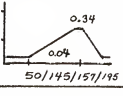
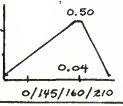
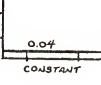
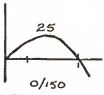
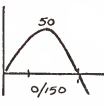
	WALL IMPEDANCE Z_w	GLOTTAL ADJUSTMENT A_g (cm ²)	CAVITY ENLARGEMENT I_e (ml/sec)	EXPIRATORY BREATH PULSE E_t (cm H ₂ O)
1	$Z_w = \text{MODERATE}$		$I_e = 0.0$	$E_t = 0.0$
2				
3				
4				
5				
6				

TABLE 5 - continued

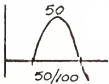
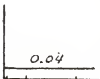
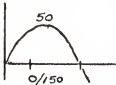
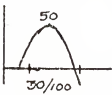
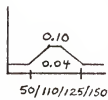

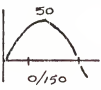
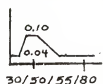

	Z_w	A_g	I_e	E_t
7	MODER- ATE			
8	$Z_w = \text{RELAXED}$		$I_e = 0.0$	$E_t = 0.0$
9				
10				
11			$I_e = 0.0$	
12				
13				
14				

TABLE 5 - continued

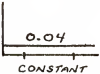
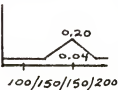
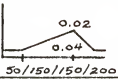
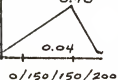
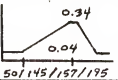
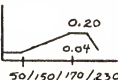
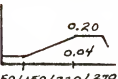
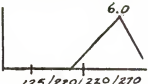
	Z_w	A_g	I_e	E_t
15	$Z_w = \text{TENSE}$		$I_e = 0.0$	$E_t = 0.0$
16				
17				
18				
19				
20				
21				

TABLE 6. Values of L_w , C_w , and R_w corresponding to the three levels of wall impedance. The values shown below were derived from impedance measurements of the cheeks made by Ishizaka et al. (1974) and an estimated total vocal tract surface area of 100 cm². These estimates agree well with those made by Rothenberg (1968, p. 93). The undamped natural frequency (F_n) of each Z_w level is also included in the table.

Z_w	L_w cm H ₂ O/L/sec ²	C_w L/cm H ₂ O	R_w Ω	F_n Hz
Relaxed	.021	.00120	8.0	32
Moderate	.081	.00084	9.3	41
Tense	.051	.00047	10.6	60

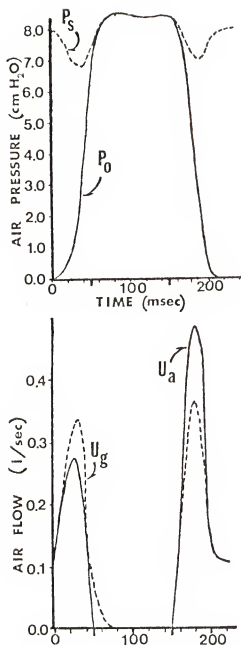


FIGURE 17. Variation in supraglottal air pressure (P_o), subglottal air pressure (P_s), and oral (U_a) and glottal (U_g) air flow during simulation of a voiceless stop (simulation no. 18).

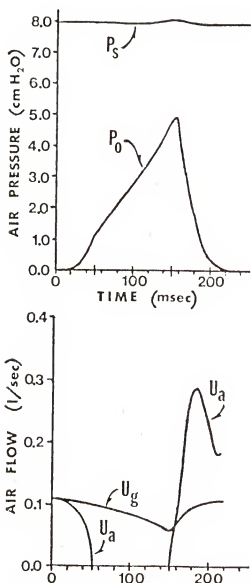


FIGURE 18. Variation in supraglottal air pressure (P_o), subglottal air pressure (P_s), an oral (U_a) and glottal (U_g) air flow during simulation of a voiced stop (simulation no. 9).

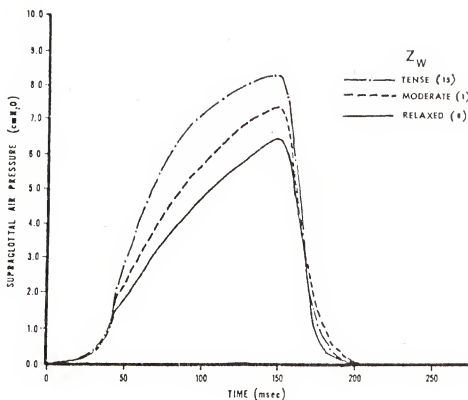


FIGURE 19. The effect of various levels of wall impedance on P_0 . See Table 6 for values of L_w , C_w and R_w corresponding to each impedance level. The numbers in the figure legend above denote each simulation as referenced in the index presented in Table 5.

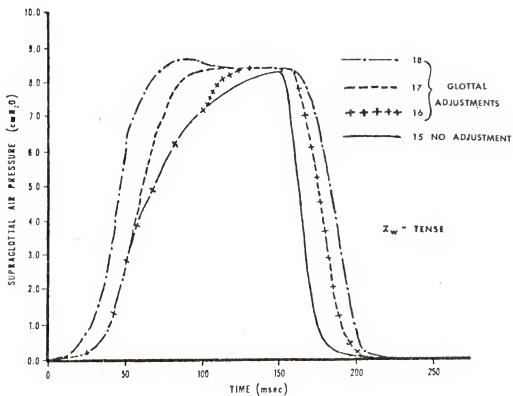


FIGURE 20. Simulations of voiceless stops with tense cavity walls and various glottal adjustments. See Tables 5 and 6 for details concerning the parameter settings used in each simulation.

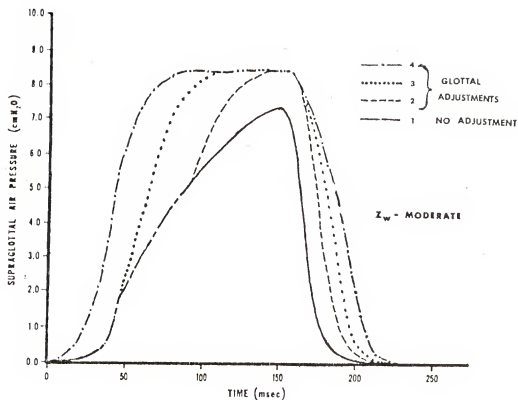


FIGURE 21. Simulations of voiceless stops with moderate wall impedance and various glottal adjustments.

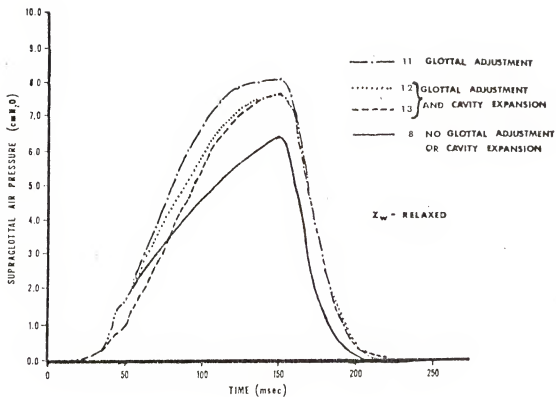


FIGURE 22. Simulations of voiced stops with relaxed cavity walls and varying degrees of cavity expansion and glottal adjustment.

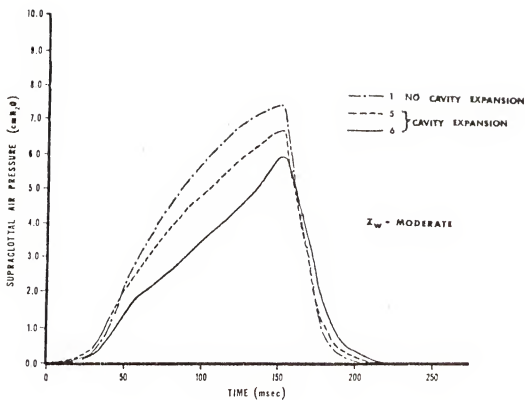


FIGURE 23. The effect of different magnitudes of active supraglottal cavity expansion (I_e) on P_o (moderate wall impedance).

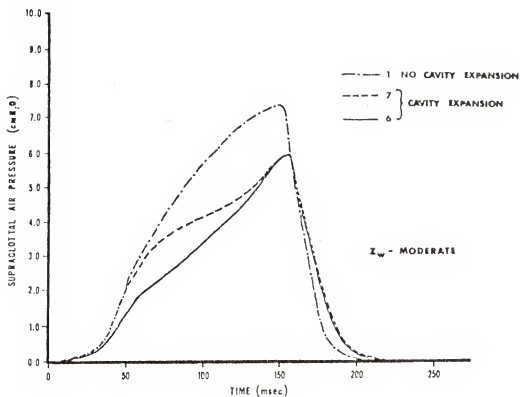


FIGURE 24. The effect of the timing of supraglottal cavity expansion (I_e) on the P_o waveform (moderate wall impedance).

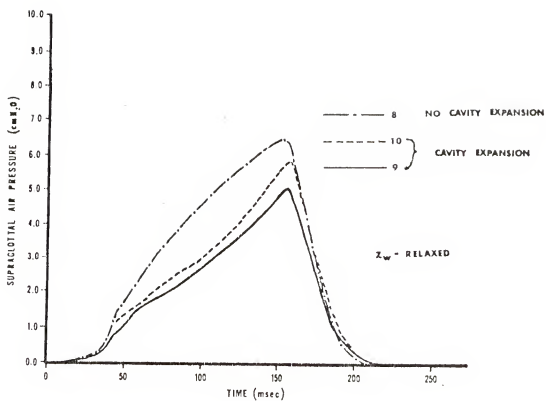


FIGURE 25. Simulations of voiced stops produced with relaxed walls and differing in the timing of I_e .

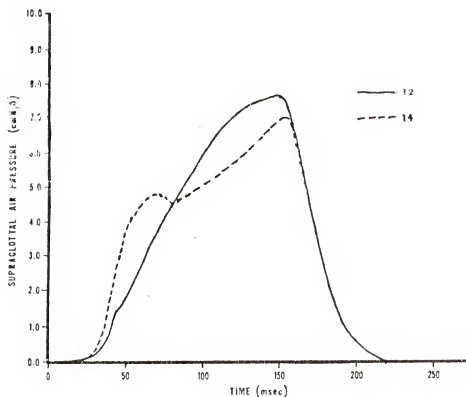


FIGURE 26. Simulation of a voiced stop with synchronous (simulation 12) and asynchronous (simulation 14) timing of cavity expansion and glottal adjustment.

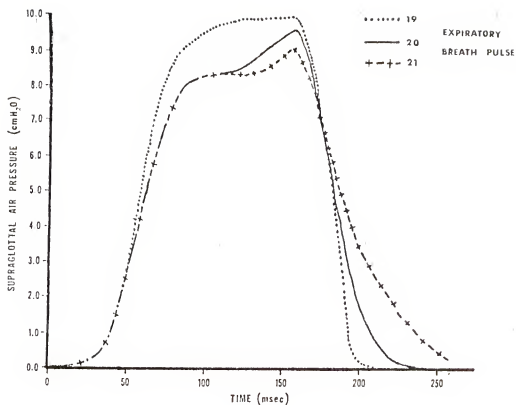


FIGURE 27. Simulations of voiceless stops produced with variously timed glottal adjustments and an expiratory breath pulse.

SUMMARY AND CONCLUSIONS

Five male subjects produced isolated VCV's -- where C was the stop consonants /p, b, t, d/ and V was the vowel /a/ or /i/ -- while wearing apparatus for the simultaneous recording of supraglottal air pressure (P_o) and air flow. The point in time when air flow reached zero (i.e., complete closure at the consonantal point of articulation) and abruptly ascended from zero (i.e., consonantal release) were identified on the P_o trace. These points were then used as a physiological reference from which other measures of the P_o waveform were made. These measurements included: The duration of the closing phase, occlusion phase and release phase; the P_o magnitude at the instant of closure and release; the peak magnitude of P_o ; and both quantitative and qualitative estimates of waveform shape. The data were analyzed using a factorial analysis of variance for both main effects and interactions (subjects X consonants X vowels).

Briefly, the following results were found:

1. The duration of the occlusion phase was remarkably stable regardless of manner of production, place of articulation or vowel environment.
2. The duration of the closing phase was generally longer when the stop was in the vowel environment /i/ as opposed to /a/. Manner and place had no systematic effect on the duration.
3. Voiceless stops had significantly longer release durations than their homorganic cognates.

4. Vowel environment and place of articulation did not have any systematic effect on the supraglottal air pressure magnitude or waveform.
5. At the instant of consonantal closure voiceless stops had significantly higher air pressures than voiced stops.
6. Voiceless stops had peak pressures greater than, or equal to their voiced cognates.
7. Peak pressure most often occurred at the instant of consonantal release.
8. Qualitatively, the supraglottal air pressure pulses had five general waveform shapes -- convex, concave, linear, bimodal and delayed.
9. None of the qualitative waveform shapes were unambiguously associated with a particular consonant class or vowel environment. However, convex waveforms were most often associated with voiceless stops, and nonconvex waveforms with voiced stops.
10. Normalized estimates of waveform shapes indicated that although pressure waveforms may sometimes appear to have qualitatively similar shapes, they are quantitatively different. Specifically, voiceless stops are quantitatively more convex.
11. Unnormalized estimates of waveform shape followed the qualitative and normalized findings with slightly less generality. Voiceless stops had either a faster rate of pressure increase during the initial portion of the occlusion phase, or a significantly slower rate during the re-

maining portion of this phase. There were no systematic differences as a function of place or vowel environment.

With the aid of a computer simulated model of stop consonant production, the articulatory implications of these results were discussed. It was concluded that:

1. The dynamic changes at the consonantal constriction were relatively independent of place and manner.
2. Voiceless stops were produced with an expiratory breath pulse.
3. The supraglottal air pressure waveforms and magnitudes reflected various articulatory mechanisms which facilitate the voicing and devoicing of stops.

A P P E N D I X

FIGURE 28. Coordinate plot (pressure versus time) of bilabial stops in the vowel environment /a/ and /i/. Each subject (S1-S5) is plotted separately. Data points represent averages over six repetitions of each VCV sample. The plotted points are connected by straight lines and represent the following pressure-time coordinates: 0.0, 0.0; P_c , T_c ; $P_c + \bar{P}_o$, $T_c + T_p$ (i.e., the intercept of α and β); P_k , $T_c + T_o$; 0.0, T_t .

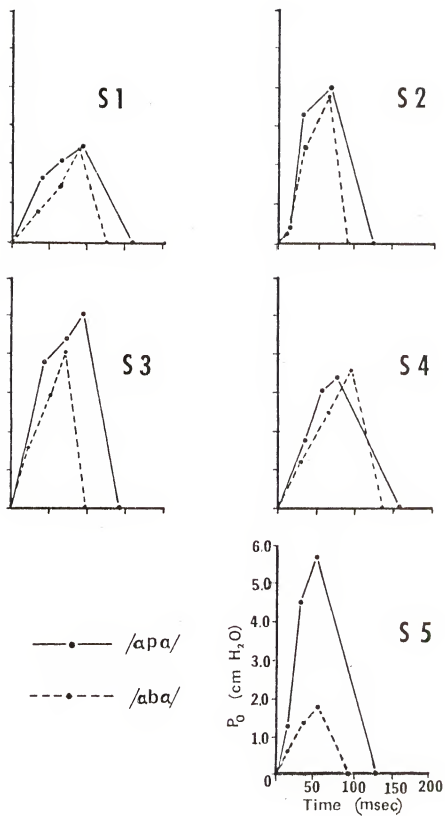


FIGURE 28

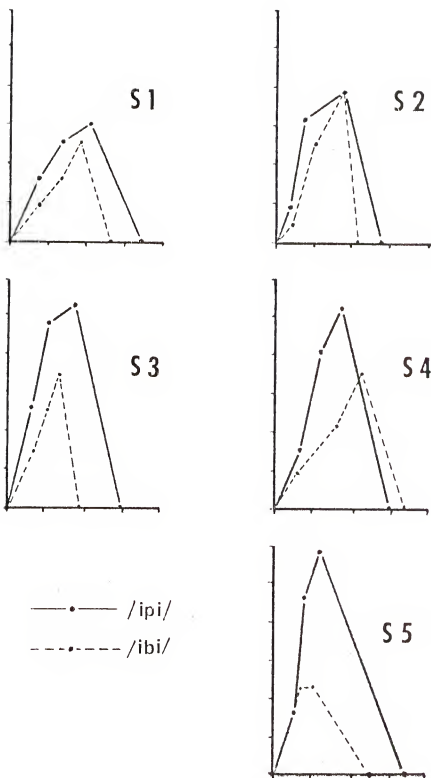


FIGURE 28 - continued

FIGURE 29. Coordinate plot (pressure versus time) of apical alveolar stops in the vowel environments /a/ and /i/. Each subject (S1-S5) is plotted separately. Data points represent averages over six repetitions of each VCV sample. The plotted points are connected by straight lines and represent the following pressure-time coordinates: 0.0, 0.0; P_c , T_c ; $P_c + P_o$, $T_c + T_p$ (i.e., the intercept of α and β); P_k , $T_c + T_o$; 0.0, T_t .

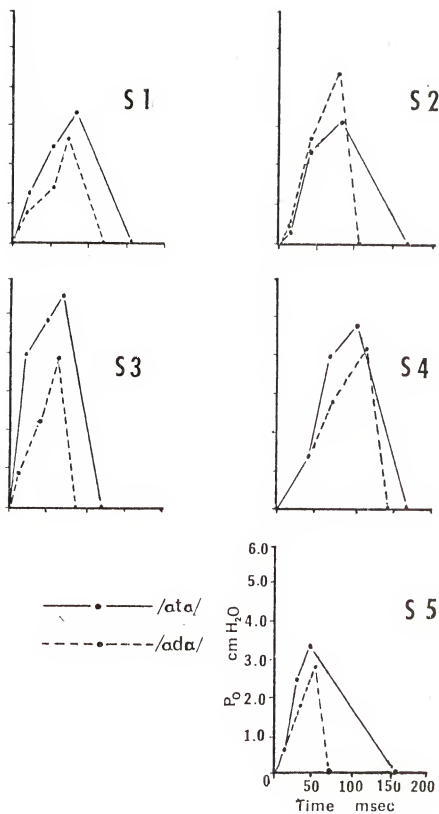


FIGURE 29

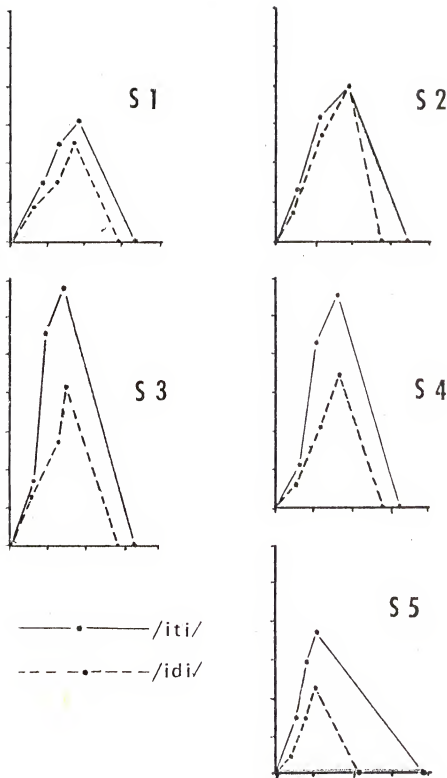


FIGURE 29 - continued

TABLE 7. Mean values of selected measurands for each subject during the production of bilabial stop consonants. Numbers in the table represent means over six repetitions of each sample.

/apa/

MEASURAND	SUBJECT #				
	1	2	3	4	5
P _c (cm H ₂ O)	3.32	0.76	7.62	3.55	2.58
T _c (msec)	84	26	84	70	30
α (cm H ₂ O/msec)	.020	.188	.020	.065	.171
XPCP (cm H ₂ O)	1.72	7.34	2.48	2.20	8.77
β (cm H ₂ O/msec)	.014	.017	.030	.013	.068
T _o (msec)	104	121	103	84	76
T _r (msec)	129	98	104	166	159
P _k (cm H ₂ O)	5.04	8.09	10.10	6.75	11.35
A (cm H ₂ O·msec)	104	704	127	343	490
TOTT (msec)	317	245	290	320	266
DIFF (cm H ₂ O/msec)	.006	.171	-.010	.052	.102

/ipi/

MEASURAND	SUBJECT #				
	1	2	3	4	5
P _c (cm H ₂ O)	3.31	1.88	5.28	3.20	3.34
T _c (msec)	74	36	60	69	51
α (cm H ₂ O/msec)	.038	.122	.130	.106	.199
XPXP (cm H ₂ O)	2.76	5.87	5.26	7.21	8.31
β (cm H ₂ O/msec)	.013	.013	.013	.038	.061
T _o (msec)	129	141	112	107	72
T _r (msec)	143	100	122	118	220
P _k (cm H ₂ O)	6.07	7.75	10.54	10.41	11.67
A (cm H ₂ O·msec)	242	644	482	536	416
TOTT (msec)	345	277	294	295	342
DIFF (cm H ₂ O/msec)	.025	.109	.118	.067	.137

TABLE 7 - continued

/aba/

MEASURAND	SUBJECT #				
	1	2	3	4	5
P _c (cm H ₂ O)	1.57	0.58	3.14	2.15	1.27
T _c (msec)	65	20	44	63	32
α (cm H ₂ O/msec)	.022	.100	.050	.046	.038
XPCP (cm H ₂ O)	3.34	7.00	4.90	5.05	2.34
β (cm H ₂ O/msec)	.041	.040	.056	.042	.026
T _o (msec)	113	114	102	132	75
T _r (msec)	72	52	49	84	89
P _k (cm H ₂ O)	4.92	7.58	8.04	7.20	3.60
A (cm H ₂ O·msec)	163	512	263	360	109
TOTT (msec)	250	186	194	279	196
DIFF (cm H ₂ O/msec)	-.019	.059	-.006	.005	.092

/ibi/

MEASURAND	SUBJECT #				
	1	2	3	4	5
P _c (cm H ₂ O)	1.89	1.09	2.92	1.88	1.48
T _c (msec)	72	41	67	68	36
α (cm H ₂ O/msec)	.022	.068	.066	.023	.073
XPCP (cm H ₂ O)	3.30	6.76	4.00	5.19	3.15
β (cm H ₂ O/msec)	.038	.037	.063	.048	.003
T _o (msec)	116	135	66	165	74
T _r (msec)	86	44	52	117	146
P _k (cm H ₂ O)	5.20	7.86	6.93	7.07	4.63
A (cm H ₂ O·msec)	166	557	146	390	148
TOTT (msec)	274	219	185	350	255
DIFF (cm H ₂ O/msec)	-.015	.031	.004	-.025	.070

TABLE 8. Mean values of selected measurands for each subject during the production of apical alveolar stop consonants. Numbers in the table represent means over six repetitions of each sample.

/ata/

MEASURAND	SUBJECT #				
	1	2	3	4	5
P _c (cm H ₂ O)	2.59	0.59	7.99	2.78	1.35
T _c (msec)	44	37	46	88	28
α (cm H ₂ O/msec)	.043	.091	.034	.103	.138
XPCP (cm H ₂ O)	4.28	5.79	2.98	6.77	5.33
β (cm H ₂ O/msec)	.030	.017	.028	.023	.046
T _o (msec)	123	131	97	122	66
T _r (msec)	148	147	105	130	223
P _k (cm H ₂ O)	6.87	6.38	10.97	9.55	6.68
A (cm H ₂ O·msec)	329	574	178	647	245
TOTT (msec)	315	342	248	340	316
DIFF (cm H ₂ O/msec)	.013	.059	.006	.080	.092

/iti/

MEASURAND	SUBJECT #				
	1	2	3	4	5
P _c (cm H ₂ O)	3.09	2.85	3.42	2.41	2.76
T _c (msec)	84	57	62	60	50
α (cm H ₂ O/msec)	.052	.066	.285	.137	.116
XPCP (cm H ₂ O)	3.19	5.29	9.85	8.67	4.71
β (cm H ₂ O/msec)	0.22	.037	.046	.045	.055
T _o (msec)	91	140	76	104	58
T _r (msec)	150	150	188	153	275
P _k (cm H ₂ O)	6.28	8.14	13.26	11.08	7.47
A (cm H ₂ O·msec)	198	531	583	672	183
TOTT (msec)	325	347	325	318	384
DIFF (cm H ₂ O/msec)	.030	.047	.239	.092	.061

TABLE 8 - continued

/ada/

MEASURAND	SUBJECT #				
	1	2	3	4	5
P _c (cm H ₂ O)	1.56	0.88	1.76	1.78	1.47
T _c (msec)	35	30	20	61	26
α (cm H ₂ O/msec)	.019	.081	.045	.046	.050
XPCP (cm H ₂ O)	3.85	8.06	6.05	6.64	4.14
β (cm H ₂ O/msec)	.067	.050	.075	.034	.052
T _o (msec)	112	126	109	175	83
T _r (msec)	87	58	49	49	38
P _k (cm H ₂ O)	5.41	8.97	7.81	8.42	5.61
A (cm H ₂ O·msec)	158	597	302	696	245
TOTT (msec)	234	214	178	286	146
DIFF (cm H ₂ O/msec)	-.047	.031	-.030	.021	-.002

/idi/

MEASURAND	SUBJECT #				
	1	2	3	4	5
P _c (cm H ₂ O)	1.86	1.48	2.58	1.20	1.02
T _c (msec)	58	46	56	56	42
α (cm H ₂ O/msec)	.023	.059	.060	.052	.054
XPCP (cm H ₂ O)	3.29	6.60	5.75	5.78	3.52
β (cm H ₂ O/msec)	.048	.034	.077	.054	.069
T _o (msec)	106	146	86	112	63
T _r (msec)	122	85	140	113	63
P _k (cm H ₂ O)	5.15	8.08	8.35	6.98	4.54
A (cm H ₂ O·msec)	152	611	243	338	183
TOTT (msec)	286	276	282	282	225
DIFF (cm H ₂ O/msec)	-.025	.025	-.017	-.002	-.015

TABLE 9. Mean values of the normalized measurands for each subject and VCV combination. Numbers represent average over six repetitions of each sample.

VCV	MEASURAND	SUBJECT #				
		1	2	3	4	5
/apa/	α^*	1.21	2.94	0.83	1.68	1.49
	β^*	0.87	0.27	1.24	0.45	0.57
	DIFF*	0.35	2.67	-0.41	1.23	0.92
	A*	.552	.803	.481	.798	.732
/ipi	α^*	1.60	2.89	2.27	1.54	1.71
	β^*	0.70	0.30	0.37	0.57	0.51
	DIFF*	0.90	2.59	1.89	0.97	1.20
	A*	.673	.781	.800	.691	.709
/aba/	α^*	0.76	1.61	0.92	1.23	1.25
	β^*	1.35	0.65	1.27	1.06	0.77
	DIFF*	-0.59	0.95	-0.35	0.17	0.49
	A*	.417	.646	.515	.586	.630
/ibi/	α^*	0.83	1.37	1.05	0.74	1.74
	β^*	1.30	0.73	0.96	1.56	-0.01
	DIFF*	-0.47	0.64	0.09	-0.82	1.75
	A*	.439	.617	.555	.444	.606
/ata/	α^*	1.25	2.02	1.10	1.80	1.66
	β^*	0.85	0.40	0.92	0.41	0.57
	DIFF*	0.40	1.62	0.17	1.39	1.09
	A*	.620	.757	.627	.774	.704
/iti/	α^*	1.51	1.68	2.22	1.62	1.42
	β^*	0.64	0.53	0.34	0.52	0.60
	DIFF*	0.86	1.15	1.89	1.10	0.82
	A*	.651	.714	.791	.731	.685
/ada/	α^*	0.54	1.27	0.81	1.18	1.05
	β^*	2.00	0.78	1.30	0.92	0.99
	DIFF*	-1.45	0.49	-0.50	0.26	0.006
	A*	.365	.585	.455	.556	.532
/idi/	α^*	0.77	1.28	0.91	1.01	0.94
	β^*	1.55	0.74	1.13	1.04	1.21
	DIFF*	-0.78	0.54	-0.22	-0.03	-0.27
	A*	.424	.629	.493	.520	.528

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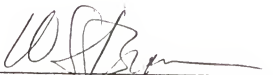
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BIOGRAPHICAL SKETCH

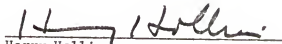
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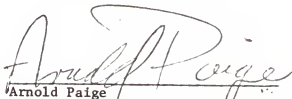
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